Optical multiple beam-forming systems for wireless communication antennas

Riza, Nabeel

Nabeel A. Riza, "Optical multiple beam-forming systems for wireless communication antennas," Proc. SPIE 2556, Wireless Communications, (18 September 1995); doi: 10.1117/12.220883

Event: SPIE's 1995 International Symposium on Optical Science, Engineering, and Instrumentation, 1995, San Diego, CA, United States

Optical Multiple Beamforming Systems for Wireless Communication Antennas

Nabeel A. Riza
Center for Research & Education in Optics and Lasers (CREOL)
and the Department of Electrical & Computer Engineering
University of Central Florida
12424 Research Parkway, Suite 400, Orlando, FL 32826

Abstract

Several new systems and concepts using optical technology are introduced for the wireless communication antenna. These include antenna-design limitations on frequency reuse in cellular architectures, optical beamforming, adaptive filtering, and direction finding, optical receive-mode IF combining, use of ultra-short optical time delay methods for millimeter wave antenna arrays, and the use of space-time coding of electro-optically steered lasers for multiple access communications.

Keywords: Optical Beamforming, Mobile Communications, Phased Array Antennas, Wireless Communications

2. Introduction

Recently, there is growing interest in the use of phased array antennas for mobile and wireless communication applications. The key reason for using phased arrays is the adaptive non-mechanical nature of these antenna systems that can generate electronically programmable transmit and receive radiation patterns based on various communication traffic scenarios. This results in increased communication channel bandwidths, lower signalling bit error rates, lower interchannel crosstalk values, and increased traffic/user capability which eventually leads to lower subscriber costs and improved service quality.

An important need for communication antennas is the generation of multiple simultaneous reconfigurable beams that operate at different carrier frequencies with independent communication/traffic channels. In some cases, based on proximity of users, frequency reuse is desirable to increase useful total channel bandwidth. Previously, we introduced and demonstrated an optical beamforming architecture that could generate phased array control signals for multiple simultaneous beams at different carriers [1-2]. This system used a laser array, a single channel Bragg cell, and a multichannel Bragg cell to generate phased array beams for N beam positions at N carrier frequencies. This system has certain limitations such as there is no element level signal amplitude and phase control that may be required in a practical antenna system for calibration. In this paper, we will describe how a multi-beam, multi-frequency optical beamformer can be formed using Bragg cells and liquid crystal devices [3]. This architecture provides the vital antenna calibration feature, and operates with tunable carriers up to C-band. This system, a vital extension of the architecture in [1-2], is particularly suited for transmit arrays, although, can be used with receive arrays by using mixer electronics or the non-linear properties of the photo-sensor array.

First we take a look at the mobile communication scenario and the impact phased array antennas can have particularly in terms of frequency reuse. We describe how optical technology can be inserted into these communication antenna systems, specifically performing all tasks optically such as beamforming, adaptive control, and direction finding. Then we introduce a specific multichannel optical beamformer for wireless and mobile communications, introducing why this new optical control technique can provide benefits to the global communication highway scenario. Other advanced optical solutions for wireless communications are also introduced later in the paper.

3. The Mobile Communication Scenario and its Needs with Respect to Phased Arrays

Today, the most common antennas used for mobile communications include omnidirectional antennas such as vertical dipoles, fixed directional dishes, and mechanically rotated/adjusted parabolics. Because of the expected explosion of mobile services and users in the next century, a cost effective smart antenna system needs to be developed that can intelligently handle the congested traffic scenarios of the future. In this paper, we propose the use of novel optical systems for forming certain smart antenna systems for mobile communications.

Fig.1(a) shows the typical mobile scenario where there are a bunch of base stations (B), with each station centered in its cell that can have a maximum of N mobiles (M). A simple scenario is the line-of-sight single surface mobile scenario such as land mobile or ship/maritime mobile where all mobiles are in a single communication plane (e.g., the sea). Satellites can also be considered in this scenario if all satellites are in the same orbital plane. In these cases, the first step is to have a two dimensional (2-D) phased array with one dimensional (1-D) electronic (E) scanning. In this way, a pencil beam is positioned in 1-D space, e.g., azimuth, while the height/elevation is adjusted mechanically and then fixed until the mobile plane of communication changes. For example, on a ship, the antenna array face is tilted up to reduce surface/sea clutter. For a full 360 degree mobile coverage, it is not practically possible to use one 2-D phased array antenna. A practical phased array with low sidelobes and no grating lobes in the scan region has a typical 120 degree sector coverage. Thus, a typical minimum design for a base station antenna with 360 degree coverage would be a 3-faced phased array, where each face is a 2-D phased array with a 1-D E-scan (see Fig.1.b). For more general out of plane applications, such as land to air/space mobile communications, a 2-D E-scanned phased array would be required for both azimuth and elevation control making a more complex and expensive antenna control system.

The N-mobiles problem is the key reason for going to phased arrays as these are the ultimate smart antennas. To explain this further, there are N mobiles in a cell, all at possibly different distances and clustering densities. All mobiles need to link up with the same base station while minimizing crosstalk among the different mobiles. In addition, we need to efficiently use the limited frequency spectrum allocated for this type of service. This means that to the extent it is possible, frequency reuse is preferred within a cell, and that each mobile should preferably not use a different frequency/carrier. One efficient way for frequency reuse is the application of spatial multiplexing via an E-scanned phased array antenna. In this case, for low density traffic where the mobiles are sufficiently separated, the same carrier could be used for all the spatial beams (Fig.2(a)); otherwise, two different carriers could be used for adjacent beams throughout the cell such that no two adjacent beams have the same frequency (see Fig.2 (b)). Because frequency is reused frequently, the job of the phased array is to prevent within cell mobile to mobile crosstalk, plus reduce base station to base station interference. Typically, all the base stations would be connected via dedicated links which could either be wideband microwave/millimeter wave links or fiber optic links. The extreme case of spectrum use is when all positions/angles in a cell correspond to different carriers, i.e., N positions and N carriers. In order to prevent cell to cell crosstalk, the aligned beams from the two nearest cells must have different carriers (see Fig.2(c)). This allows each base station to distinguish that for a particular beam angle it should hear a particular carrier. All this is fine but a practical antenna array face has a limited hearing capability as shown earlier in Fig.1(b), where antenna 1 essentially cannot hear antenna 2 or antenna 3 sector angle mobile signals. Thus, efficient frequency reuse can be adopted just because of the 3-face design structure of phased arrays. Fig.3 shows how frequency can be reused within a cell, with each sector/antenna having N carriers for N beam positions. Note that the carriers at the edges of the sectors are designed to be different to prevent cell to cell crosstalk. The previous discussion assumes that there is only one mobile per antenna beam position. To be completely general, it is possible to have more than one mobile per antenna beam position/angle. In this case, mobiles at the same beam angle must use different sub-carriers. Thus, for ultimate reduction in mobile to mobile crosstalk within an antenna sector in a cell, the N mobiles in the sector must use N different carriers. This means that if an antenna sector is divided into a maximum of M different beam positions (N can be more or less than M), then M separate beamfomers are required for the single faced phased array to form M simultaneous beams. Recall, each beam can have many sub-carriers corresponding to different mobiles at the same beam angle. These sub-carriers can be separated via a bank of parallel electronic filters. All this means that there is a heavy price to pay for all the beamforming hardware which leads us to the next section regarding the use of optics to lighten this hardware burden.

4. Insertion of Optical Technology in Mobile Communication Antenna Systems

The conclusion of the previous discussion is that for mobile communications, a phased array antenna must have simultaneous, multi-carrier, multi-beamforming capabilities for both the transmit and receive functions of the antenna. Because most high performance communication systems use separate antennas for transmit and receive modes to avoid feedthrough, and because simultaneous transmit and receive operation will be required for mobile communications, separate beamformers are needed for the simultaneous transmit and receive modes. This means that a lot of duplicative antenna control hardware is required, implying that the system will become large, heavy, expensive, power hungry, EMI prone, and a possible environmental hazard as many of these systems will be deployed for global coverage of communication services.

Recently, there is a growing interest in wirelesss and mobile communications [4,5], and in particular, the use of phased array antennas and adaptive phased arrays for the mobile problem, particularly for the base stations [6-11]. The use of fiber-optics has also been proposed for feed and distribution systems for microcelluar radio based on micro-cells [12-14]. In addition, the use of optical beamfoming has also been suggested for personal mobile communications, in particular, for satellite and land radio platforms [2, 15-17]. In this paper, we propose the use of optics not only for beamforming, but also for adaptive control, direction finding, and ambiguity function processing for the mobile communication application (see Fig.4). The driving force for employing optics lies in the parallelism of the optical processors and the multi-channel nature of the N-mobile problem. It is hoped that by using the correct mix of optical and electronic technology, the antenna system designer can design a smart system with the highest degree of cost, size, and weight saving for a given performance.

5. Optical Recognition, Direction Finding, Adaptive Control Technology for the Mobile Application

The use of a target recognizer with a mobile communication antenna such as a land radio base station can be very useful as mobiles in the antenna sector can be identified as targets much like a radar, thus giving vital range and mobile speed information that can be used to adjust antenna beam gains and other array control parameters. In other words, the communication antenna is from time to time operated as a radar for judging the traffic scenarios. The phased array antenna radar return signal after receive beamforming is fed into an ambiguity function processor, also called a range-doppler processor. This processor is basically a two dimensional correlator that outputs the target information in a 2-D range-doppler bin format. Acousto-optic (AO) processors can also be used for direction finding. In this case, signal returns from a set of auxilliary channels from the phased array before receive beamforming are fed to a multichannel AO device that implements a 2-D optical spectrum analyzer with the spatial output being the carrier frequency and the azimuth coordinate of the mobiles. Optical ambiguity function processors and direction finders are useful because they can handle many simultaneous targets/mobiles using a compact, low power processor using a few Bragg cells [18]. Adaptive phased arrays require weight generation hardware. Typically, this hardware is made up of multichannel correlators for weight generation and convolvers for error signal or residue generation. The use of optics for antenna array adaptive filtering/nulling is considered promising because a large number of wideband nulls can be generated using a potentially compact and low power processor, again based on a few Bragg cell devices [19]. Note that for both the direction finder and adaptive nuller application for wireless communications, the target enviroment is in general not as hostile and long range as in the military scene. This means that the processor requirements can be less severe than that for a military application where false alarms cannot be tolerated. Recently, we have developed some novel compact optical architectures for spectrum analysis, correlation, convolution, and complex array processing/transversal filtering using Bragg cells that can be applied to the mobile recognition, direction finding, and adaptive filtering applications [20-23]. Multichannel versions of these systems could be used for a variety of signal processing tasks associated with mobile communications. Fig.5(a) shows a novel adaptive processor design for broadband beam nulling, while Fig.5(b) shows a narrowband transversal filter. Later work will describe specific results from these systems in relation to mobile communications. In the rest of this section, we will focus on optical beamforming technology; in particular, narrowband phase-based array processing as most communication scenarios are narrowband in nature.

5.1 Multi-beam Multi-Frequency Optical Beamformers

The objective is to form P independent antenna beams at P different carrier frequencies for P communication channels. This means that for an N-element antenna array, we need P independent phase-based beamformers, each have N phase shifters and N amplitude trimmers (or gain control devices). The required carriers are application dependent. For example, Commercial Cellular: 850-900 MHz; Personal Communications Band: 1.850-1.990 GHz; Land Mobile Radio: 150, 350, 850 MHz; Iridium Satellite (Voice, data): 1616-1626.5 MHz; LEOSAT: 148-149 MHz, and ODYSSEY (TRW-RDSS): 29.5-30 GHz [4]. Because the carriers can vary from the 100's of MHz domain to several tens of GHz (mm-wave domain), the optimum approach to beamforming might be different.

Fig.6 and 7 show the block diagrams as to how optics can be used for multi-beam formation for the transmit and receive antennas, respectively, while Fig.8 shows the type of photosensor used in the receive array. Note that the receive array is some what more complex than the transmit array. Thus, particularly for broadcast applications, e.g., satellite video/TV and paging, the optical beamformer has strong benefits over an all-electronic beamformer in terms of reduction in hardware size, weight, control power, and EMI. Fig.9(a,b) shows a transmit array optical beamformer using dual laser heterodyning for tunable carrier generation and a pair of spatial light modulators for the antenna element level control functions. The key thing to note is the use of a pair of compact low loss 2-D nematic liquid crystal (NLC) arrays for all the optical phase shifters and amplitude trimmers for the entire multi-beam antenna. For a 100 element array with 30 beams, this would be 3000 phase shifters and 3000 amplitude trimmers. Because, most mobile communication applications do not require fast beam switching, the moderate (1 ms) response time of NLCs is adequate. It is also possible to use the much faster (e.g., 10 ns speed) although less mature multiple quantum well devices instead of the NLCs, as will be demonstrated later. Also note the use of free-space optics (a cylinder & moving diffuser) for combining the signals for the P beams; thus saving space and extra rf beam combining hardware. The moving diffuser reduces the mutual coherence of the adding laser beam, as is required for a linear rf summation via a non-linear photo-sensor. When using dual-lasers for carrier generation, it is necessary to have high quality phase-locking electronics for low phase noise carrier generation, in addition to narrow linewidth lasers. So far, up to 60 GHz signals have been generated by this method (Lightwave Corp.). There are several features of the design in Figures 6-8. These are: independent wide tunable carriers (DC -100 GHz), essentially frequency insensitive beamformer hardware, multi-channel stackable design for a large number (e.g., 50) of multiple independent beams, modular beamformer design -- Antenna control channels can easily be increased, low cost per control channel via SLM-based design, compact light weight design for high platform mobility, optical fiber-based remoting capability for low EMI, full calibration capability up to 10 bits -- both amplitude & phase, and reduction in rf networks via bulk-optical combining and splitting -- Leads to ease in simultaneous multiple beamforming. A thing to note with the receive beamformer is that the high speed photo-sensor array acts both as an optical to rf converter array and an electronic mixer array. In otherwords, each photo-sensor is a three terminal device such as a photo-transistor. This efficient design, shown in Fig.8 prevents adding another electronic mixer per antenna element for generation of the IF signals produced in the receive mode. Recently, this device configuration has been demonstrated [24].

There are many mobile communication applications requiring C-band or less carriers. Because most mobile array antennas have a moderately small number of elements (e.g., < 100 elements), and are low power/wattage systems compared to radars that have a long range of coverage (e.g., each base station antenna operates within its sector within its cell; a cell could have 3 or more sectors because of the 3 faced antenna design), an alternative way using Bragg cells can be used for carrier generation. In this case, we do away with the expensive phase locking electronics and the requirement for extremely low linewidth coherent lasers. Nevertheless, the key limitation we acquire is the limited C-band and below carrier range capability, unless we use additional mixer and filter electronics [26]. This Bragg cell based multi-beam system is shown in Fig.10. Note how the frequency deflection property of the two Bragg cells is utilized to form the P spatially separated system channels that operate at the different carriers. Because we are using single channel Bragg cells that are driven by an electronic sum of different carrier signals, there is the possibility of intermodulation product generation by the non-linear regime of the Bragg cells, depending on how hard you drive the Bragg cells. To some extent, it is possible to choose the carriers and use spatial filtering to block the unwanted spurious signals. Nevertheless, the safest option is to replace the single channel Bragg cells with P channel Bragg cells (see Fig.11). In this case, the channel signal modulations can be introduced by modulating the P-element input laser array instead of using the electrooptic modulators as in the single channel AOD design. Note that because of the in-line design of these systems, the lasers can be broadband high power devices.

6. Advanced Optical Concepts in Mobile Communication Antenna Arrays

Advances and improvements in laser arrays in relation to size, cost, modulation speed, power, efficiency, and packaging can lead to further innovations in optical beamformer designs. One good example is the use of two dimemsional laser arrays such as vertical cavity surface emitting laser arrays (VCSELAs) for compact receive beam combining using free-space optics. As shown in Fig.7, for optimum performance, P receive beams require P IF/electrical combiners with N:1 powers. Fig.12 shows how a laser array with N mutually incoherent lasers can be used to directly modulate the N receive IF signals from one receive system channel using a simple lens, moving diffuser, and IF-band photosensor used to do the N:1 signal summation and generation. Because laser modulation at lower frequencies is easier and more efficient than at the much higher receive bands, P optical IF combiners can be efficient, in addition to being compact and EMI insensitive when compared to P electrical N:1 IF combiners.

Because of the possible use of microcell architectures for mobile communications where the maximum distance from a microcell to a base-station is 10 km, the use of low loss fibers can allow antenna remote control via a central optical command and control center. In otherwords, a large portion of the optical antenna control hardware for L base station antennas can be located at one central location. This will benefit the repair and monitoring of the total antenna control hardware, plus making the remotely controlled antenna units more mobile and less power hungry due to their smaller size & weight.

All previous discussions have focussed on using phased arrays for the larger base station antennas, that are relatively fixed or for mobile platforms such as ships, trains, etc, that have sufficiently large power and size handling capabilities. With the increasing use of GPS (Global Positioning Satellite) technology on mobile platforms, it is conceiveable that smaller platforms such as automobiles can use phased array antenna technology for communications. Because of the platform size limitations, it is a must to use the high end of the radio spectrum, i.e, millimeter wave (e.g., 35 GHz) carriers because this leads to smaller antennas. This is a perfect example where optical beamforming technology can play a key role as the added benefits of optics such as low EMI and low rf hazards can be critical when human proximity to the antenna is a key safety concern as in automobiles. Because of the mm-wave nature of the carriers where maximum phase shifts required are relatively short free-space/solid optics delays (< 1 cm), it is considered viable to use optical time delay techniques (instead of the optical heterodyning methods) for making compact antenna $0\text{-}2\pi$ phase controllers. Earlier, we have described various optical time delay methods using laser arrays, optical polarization 2-D switching arrays coupled with polarization sensitive bulk optics for making relatively long delays (e.g., 0.5 to 4 ns) for large microwave radar systems [26]. Fig.13 (a-d) shows some extensions of these optical delay structures for generating very short optical delays required for the mm-wave communications phased array application. These short delays can be introduced through relative path delays for light passing through free-space and isotropic crystals (e.g., glass in a deflected path) or through uniaxial crystals in the in-line straight path. Note that because of the free-space/solid optics nature of these systems and the use of 2-D laser arrays like VCSELAs, the formation of multiple antenna beams becomes easier.

Moving to even higher frequencies in the electromagnetic spectrum such as the optical band (e.g., 532 nm, 1060 nm, 1300 nm, 10.6 μm laser wavelengths) can be useful in some mobile communication applications such as point-to-point multiple access communication between base stations located at roof tops of high rise buildings such as New York's Manhattan district. Optical antennas will allow the use of ultra-wide bandwidths for communications, plus causing minimum interference with other base stations because of the narrow beamwidth of the lasers. Instead of using mechanical steering of the laser beams for multiple access, it is possible to use electro-optical steering of the laser beam [27]. Such optical beam steering can be implemented with tiny optical phase control arrays, much like the ones used for the previously mentioned optical beamformers for microwave phased array antennas. Recently, we have developed simple optical beam control devices that could be used for this optical steering application [28]. Moreover, we have earlier proposed the use of space-time code division multiple access (CDMA) for optical laser beams for communications. This technique where the optical aperture of the beam is spatially codedusing an SLM can be addedto the optical phased array steering system to give it advanced multiple access features that are not possible when just using temporal multiple access methods like FDMA, TDMA, and CDMA. Nevertheless, when using the optical medium for communications, there can be limitations such as weather and atmospheric effects. Satellite to satellite multiple access could alleviate these problems, but add others such as radiation hardening and extreme temperature swing effects.

7. Conclusion

This paper has introduced several new systems and concepts for the use of optical technology in wireless mobile communications. These include the practical aspects of phased array antenna design on frequency reuse and cell design in cellular communications, the use of all-optical processors for mobile recognition, adaptive weight generation, and direction finding, and the use of SLM-based heterodyning optical processors for multi-beam, multi-frequency antenna control including C-band and below controllers using Bragg cell technology. In addition, we have also proposed the use of 2-D laser arrays and free-space optics for IF receive beam combining, the use of ultra-short optical time delay techniques for mm-wave antennas for small mobile platforms such as cars, and the use of electro-optically steered laser phased arrays for multiple access communications using a unique space-time CDMA technique.

8. References

[1] N. A. Riza, Ph.D Thesis, Ch. 6, Caltech., 1989.

[2] N. A. Riza, `` An acoustooptic phased array antenna beamformer for multiple simultaneous beam generation," *IEEE Photonic Tech. Letters*, Vol. 4, No.7, pp.807-809, July 1992.

[3] N. A. Riza, `` A compact high performance optical control system for phased array radars," *IEEE Photonic Tech. Letters*, Vol. 4, pp.1073-1076, Sept., 1992.

[4] See Special Issue on *Wireless Networks for Mobile and Personal Communications*, *Proc. of the IEEE*, Sept., 1994.

[5] R. H. Katz, `` Adaptation and mobility in wireless information systems,'' *IEEE Personal Communications Magazine*, First Quarter, p.6-17, 1994.

[6] S. C. Swales, M. A. Beach, D. J. Edwards, and J. P. Mcgeehan `` The performance enhancement of multi-beam adaptive base station antennas for cellular land mobile radio systems, '' *IEEE Trans. on Veh. Tech.*, Vol.39, No.1, pp.56-67, 1990.

[7] M. A. Beach, P. Guemas, and A. R. Nix, `` Capacity and service extension for wireless networks using adaptive antennas,'' *Electronics Letters*, Vol.30, No.22, pp.1813-1814, Oct., 1994.

[8] T. L. Doumi and J. G. Gardiner,`` Use of base station antenna diversity for mobile speed estimation,'' *Electronics Letters*, Vol.30, No.22, pp.1835-1836, Oct., 1994.

[9] M. Klemes and G. K. Chan, `` Reducing frequency reuse distance with adaptive base station antennas in mobile communications,'' Proc. of the IEEE Conf. on Adaptive Antennas, pp.21-26, Nov., Melville, New York, 1994.

[10] D. Gerlach and A. Paulraj, `` Adaptive transmitting antenna arrays with feedback,'' *IEEE Signal Processing Lett.*, Vol.1, No.10, Oct., 1994.

[11] T. Gebauer and H. G. Gockler, `` Channel-individual adaptive beamforming for mobile satellite communications,'' *IEEE Journal on Selected Areas in Communications*, Vol.13, No.2, Feb., 1995.

[12] T-S Chu and M. J. Gans, `` Fiber optic microcellular radio,'' *IEEE Trans. on Veh. Tech.*, Vol.40, No.3, pp.599-606, Aug., 1991.

[13] M. Shibutani, T. Kanai, W. Domom, K. Emura, and J. Namiki, `` Optical fiber feeder for microcellular mobile communication systems (H-015),'' *IEEE Journal on Selected Areas in Communications*, Vol.11, No.7, Sept., 1993.

[14] J. Wu, J-S Wu, and H-W. Tsao, `` A fiber distribution system for microcellular radio,'' *IEEE Photonics Tech. Lett.*, Vol.6, No.9, Sept., 1994.

[15] M. J. Wales, C. Edge, M. Holliday, R. Walker, W. S. Birkmayer, B. Hosselbarth, and T. Jakob, `` Optoelectronic beamforming network for a space-borne phased array antenna,'' *SPIE Proc.*, Vol. 1703, Orlando, Florida, 1992.

[16] D. K. Paul, ``Optical technology in satellite communications,'' *SPIE Proc.*, Vol.1953, pp.216-226, 1993.

[17] K. Horikawa, M. Shimizu, and H. Ogawa, `` Optically controlled multiple beamforming and steering network for phased array antenna,'' *SPIE Proc.*, Vol.2155, pp.325-334, Los Angeles, California, 1994.
[18] E. A. Viveiros, L. J. Harrison, R. J. Berinato, and R. A. Durrett, `` Acousto-optic range doppler processor insertion into an advanced spread spectrum radar,'' *SPIE Proc.*, Vol. 2236, pp.39-45, Orlando, Florida, 1994.
[19] R. M. Iodice and P. H. Ruterbusch, `` Acousto-optic null steering processor (AONSP): initial hardware results and observations,'' *SPIE Proc.*, Vol. 2236, pp.76-80, Orlando, Florida, 1994.
[20] N. A. Riza, `` In-line interferometric time integrating acoustooptic correlator,'' *Applied Optics*, Vol.33, No.14, pp.3060-3069, may 10, 1994.
[21] N. A. Riza, `` Space Integrating Interferometric Acousto-optic Convolver,'' *IEEE Photonic Technology Letters*, Vol.7, No.3, pp. 339-341, 1995.
[22] N. A. Riza, ``Optically efficient interferometric acousto-optic architecture for spectrum analysis," *Applied Optics*, Vol.31, No.17, pp.3194-3196, June 10, 1992.
[23] N. A. Riza, `` Liquid crystal-based optical controllers for phased array antennas," *SPIE Proc.*, Vol. 2155, pp.169-180, Los Angeles, CA, 1994.
[24] C. Rauscher and K. J. Williams, `` Heterodyne reception of millimeter wave modulated optical signals with an In P-based transistor,'' *IEEE Trans. Microwave Theory & Techniques*, Vol.42, No.11, Nov., 1994.
[25] N. A. Riza, `` Acousto-optic liquid crystal analog beamfomer for phased array antennas," *Applied Optics* , Vol. 33, No.17, pp.3712-3724, June 10, 1994.
[26] N. A. Riza, ``Liquid crystal-based optical time delay units for phased array antennas,'' *IEEE/OSA Journal of Lightwave Tech* , Vol.12, No.8, August, 1994.
[27] K. J. Banard, E. A. Watson, and P. F. McManamon,`` Non-mechanical microscanning using optical space-fed phased arrays,'' *Optical Engineering*, Vol.33, No.9, pp.3063-3071, 1994.
[28] N. A. Riza and M. C. DeJule, `` Three terminal adaptive nematic liquid crystal lens device'' *Optics Letters*, Vol.19, No.14, pp. 1013-15, July, 1994.
[29]N. A. Riza, J. E. Hershey, and A. A. Hassan `` A signaling system for multiple access laser communications and interference protection`` *Applied Optics* , Vol. 32, No. 11, pp. 1965-1972, April 10, 1993.

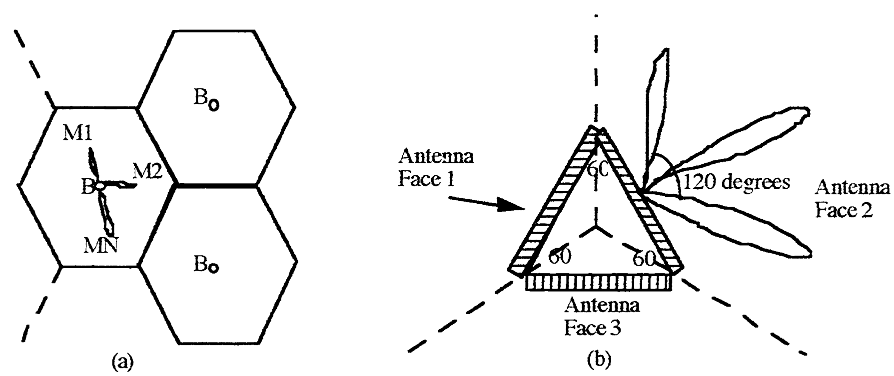

Fig.1 (a) The typical N-mobiles per cell scenario, with each cell having a base-station; (b) 3 face phased array antenna design for full 360 degree coverage of a cell. This figure also shows the hearing limitations of a 3-face phased array.

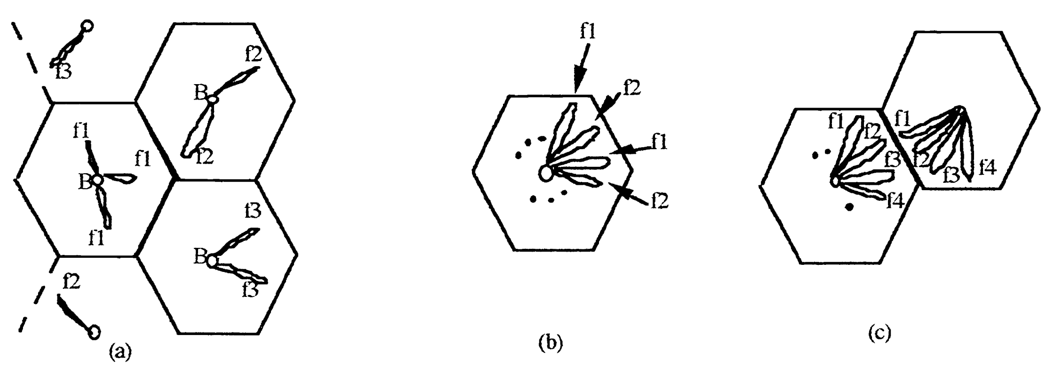

Fig.2 (a) Full carrier reuse per cell when all mobiles are sufficiently apart; (b) Two carrier frequencies used per cell with alternating carriers per beam position; and (c) N carriers for N mobiles corresponding to N different beam positions per cell.

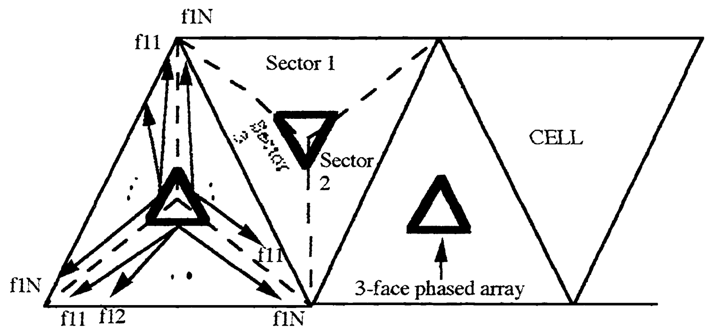

Fig.3 Frequency reuse within a cell, with N carriers per sector and 3 sectors per cell.

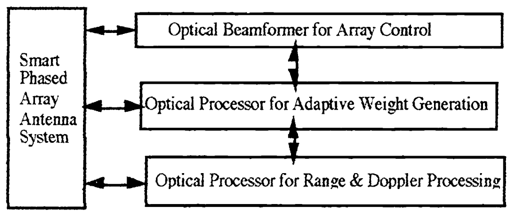

Fig.4 All-optical antenna control system with advanced signal processing for a wireless phased array antenna.

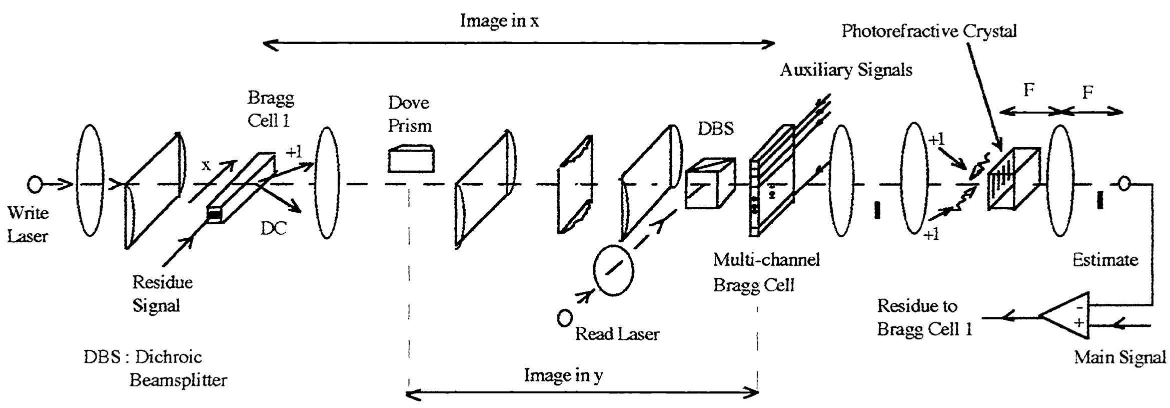

Fig.5(a)The novel acousto-optic adaptive beamformer for null steering and broadband processing.

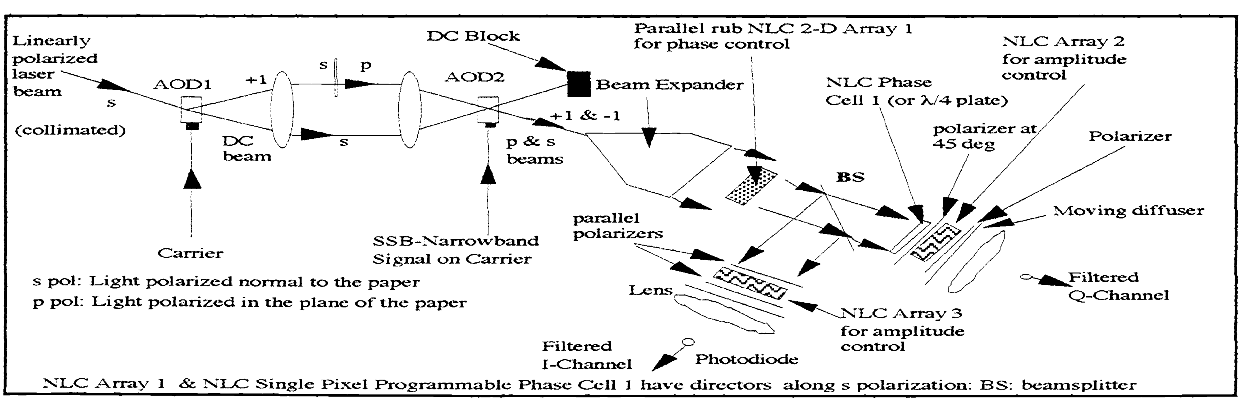

Fig.5(b) The single channel optical architecture for Narrowband Complex Array Signal Processing and Transversal Filtering.

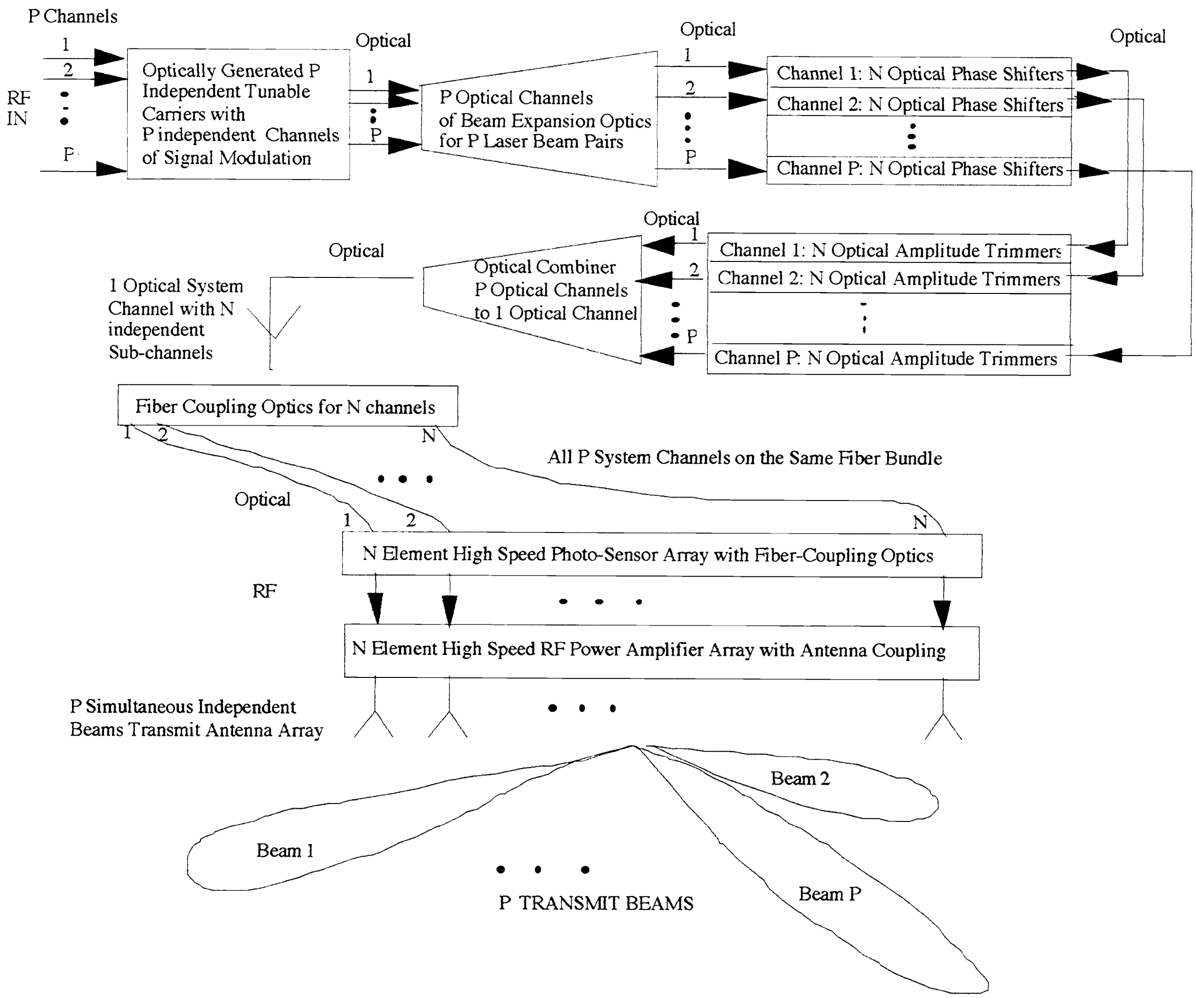

Fig.6 Optical Beamformer Block Diagram for a Transmit Array.

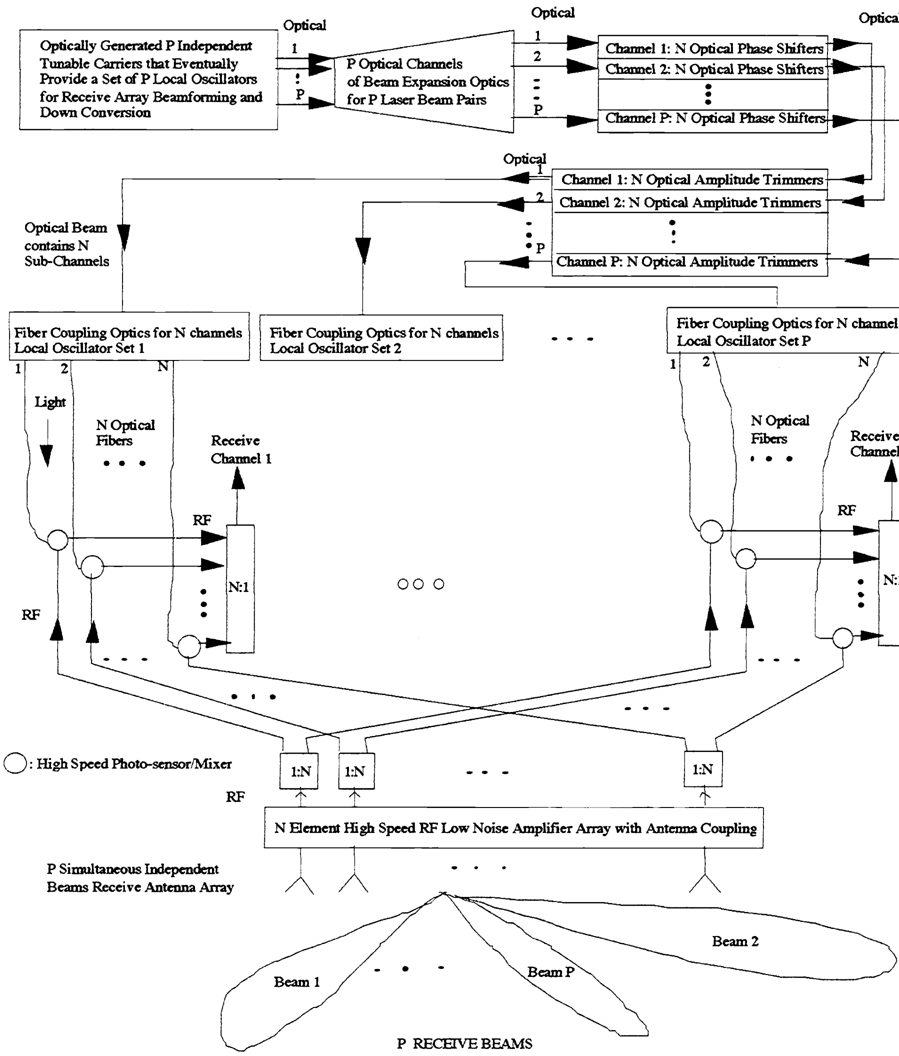

Fig.7 Optical Beamformer Block Diagram for a Receive Array.

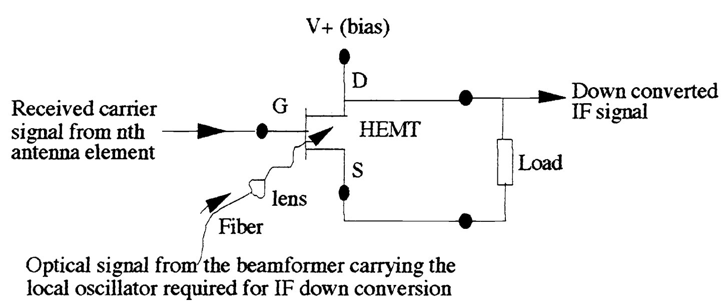

Fig.8 The photosensor/photo-transistor configuration that acts both as a optical-to-rf converter & a rf mixer. e.g.,HEMT.

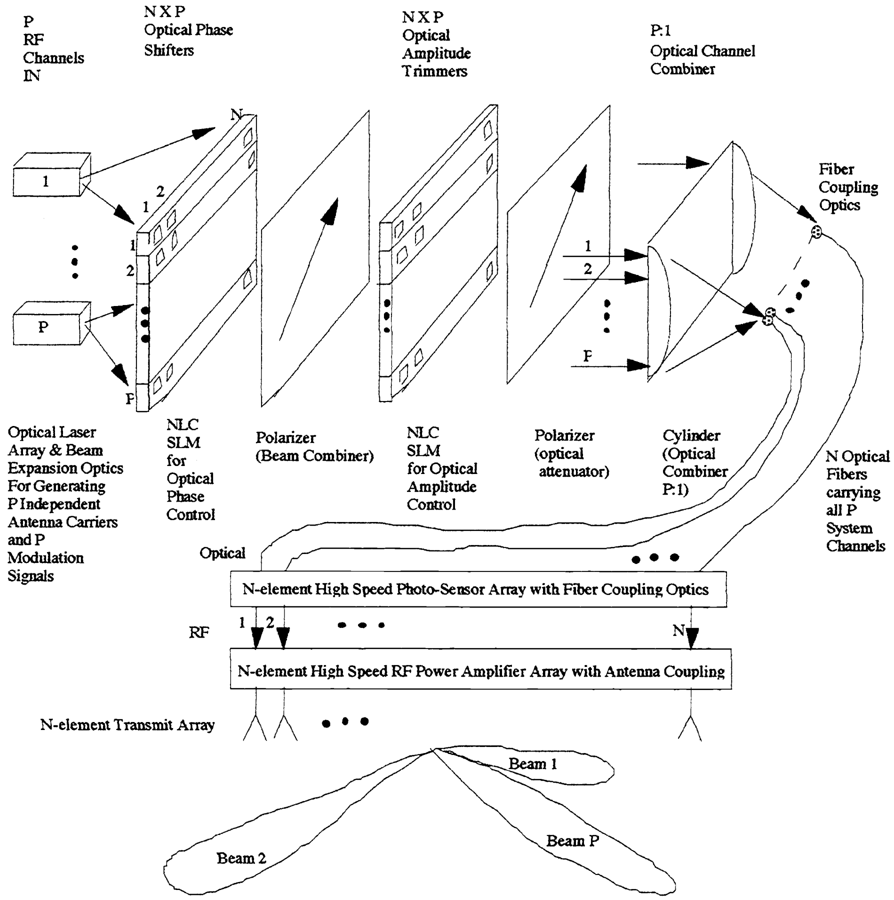

Fig.9(a) Multi-carrier Multi-beam Transmit Phased Array Optical Beamformer Basic System Diagram-based on Laser Heterodyning and SLMs for phase and amplitude control.

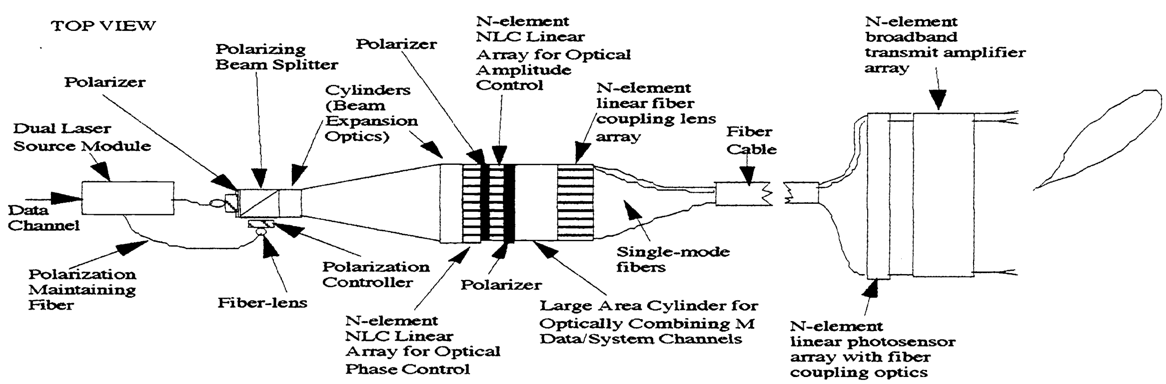

Fig.9(b) Ultracompact beamformer design for the beamformer in Fig.9(a).

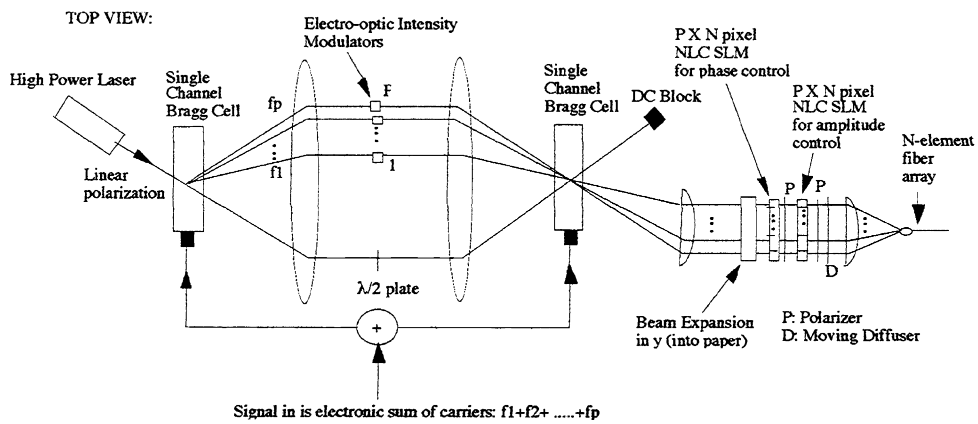

Fig.10 Single channel AOD-based Multi-beam multi-carrier optical beamformer for up-to C-band wireless antenna arrays.

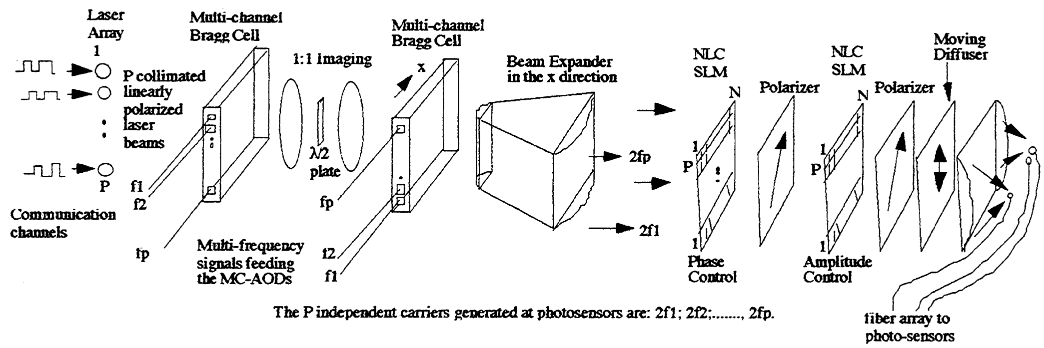

Fig.11 Multi-channel AOD-based Multi-beam multi-carrier optical beamformer for up-to C-band wireless antenna arrays.

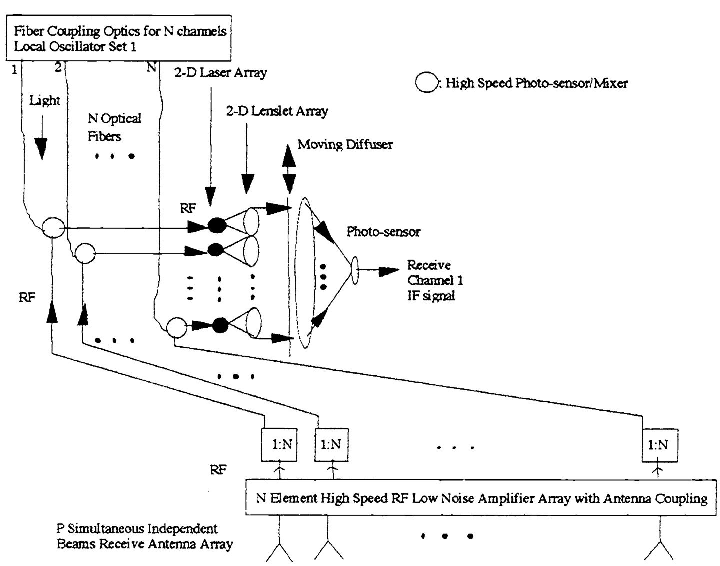

Fig.12 A compact optical combiner using an N-element 2-D laser array and free-space/solid optics for the N IF receive signals per system channel. P such optical receivers are required per antenna system. (e.g., N=100 and P=30; all 3000 lasers can be on the same substrate)

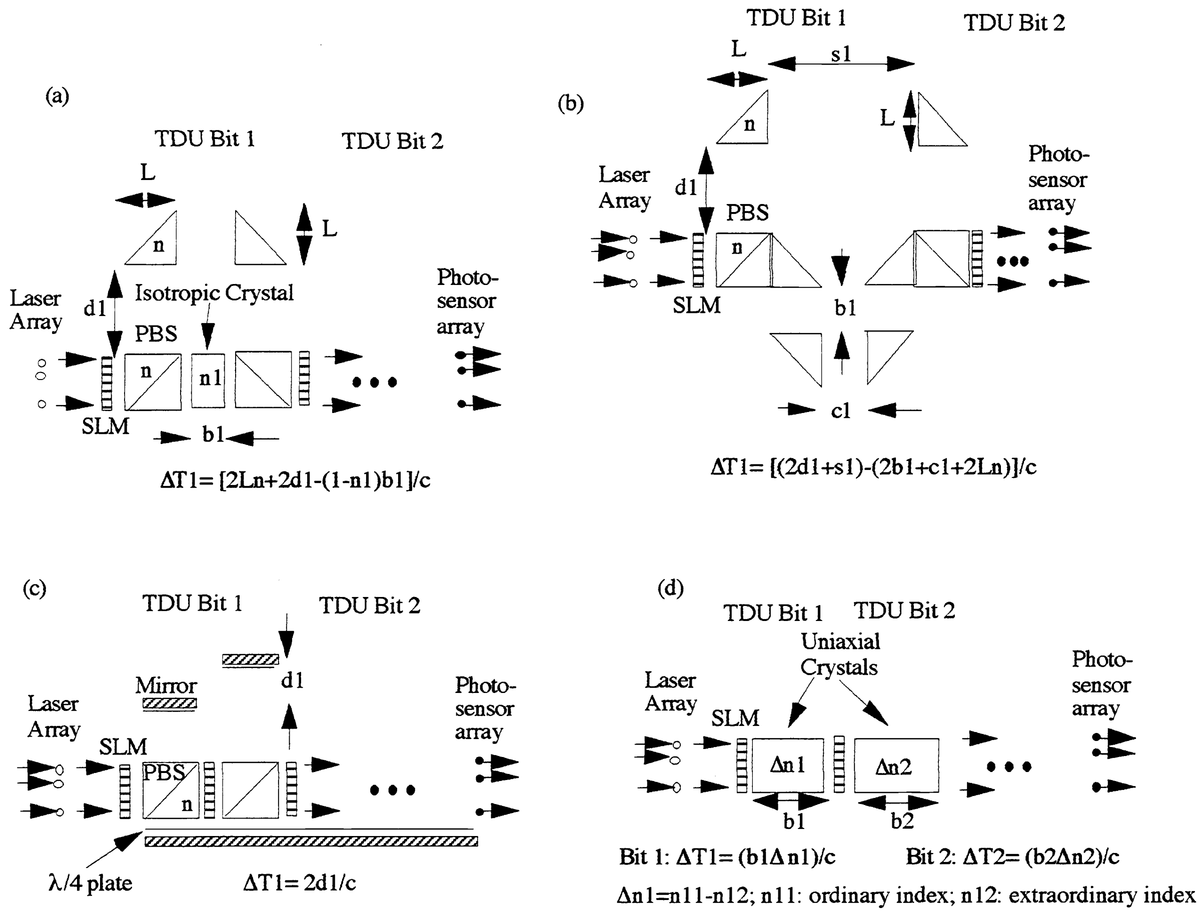

Fig. 13 Multichannel ultra-short N-bit optical time delay generation with 2-D polarization switching SLMs, 2-D laser arrays, and (a, b, c) Free-space and Isotropic crystals (d) uniaxial crystals, for mm-wave control of mobile communication phased arrays. Unlike the previous phase-based optical controllers, these systems are reversible in nature (i.e., same optical flow used for both transmit arrays and receive arrays.) Note that these systems use more components as the bits required increase.